Rotor Design Optimization Tools and Cost Models

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Rotor Design Optimization Tools and Cost Models

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Wind Energy Department
Technical University of Denmark

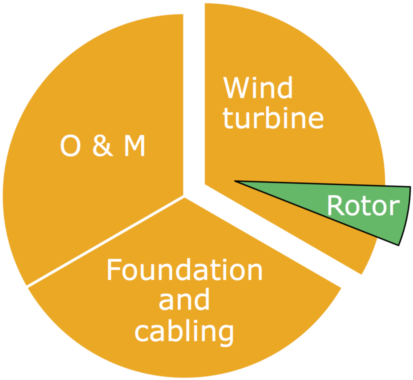
IQPC Workshop for Advances in Rotor Blades
for Wind Turbines
24-26 February 2015
Bremen, Germany

Cost of Energy

$$COE = \frac{FCR(BOS + TCC) + AOE}{AEP} \quad (1)$$

Where COE is cost of energy, BOS is balance of station cost, TCC is turbine capital cost, FCR is the fixed charge rate to annualize investment costs, AOE is the annual operating expense, and AEP is the annual energy production.

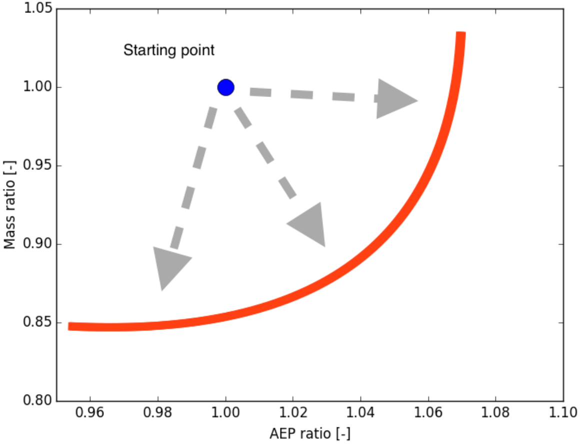
Introduction
Cost of Energy



Cost Modelling

- Correctly capturing the individual cost drivers is essential for determining how to reduce CoE.
- Component costs are very individual for each manufacturer.
- The design of the rotor has significant implications for the cost of the entire system, e.g. tower sizing, drive train.
- In this work we will try to focus on the underlying physical quantities related to the rotor design, which are major drivers for the entire system.

Cost Modelling
Blade Design Trade-Offs



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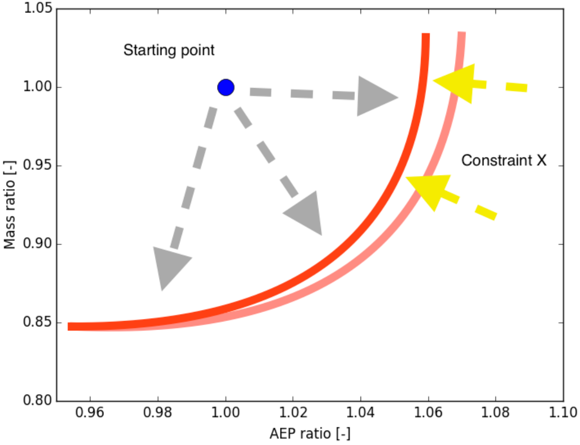

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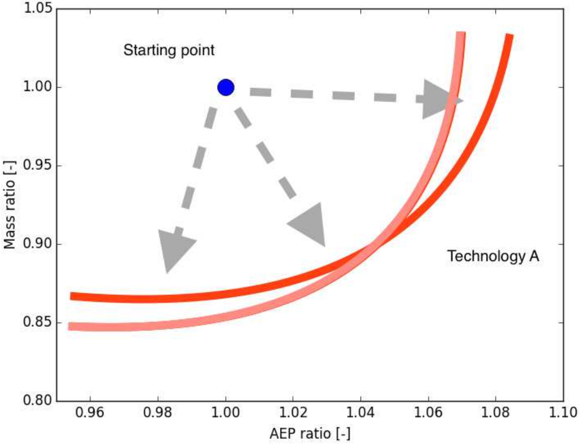

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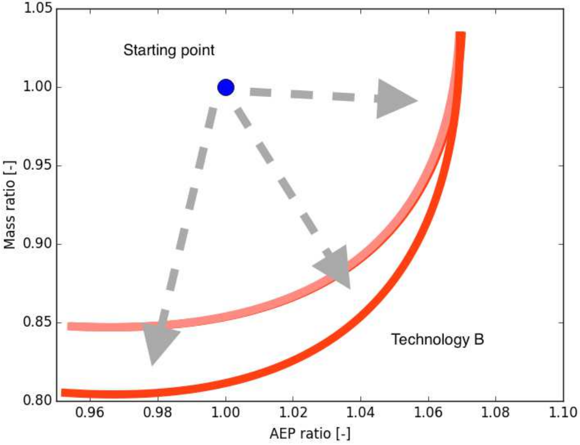

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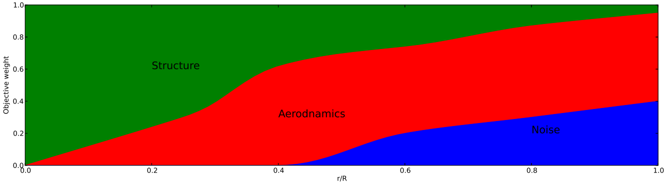


This Talk

This talk will discuss the efforts currently in progress towards realizing an *Integrated Framework For Optimization of Wind Turbines* at DTU Wind Energy and its application to the design of a 10 MW wind turbine rotor.

Cost Modelling
This Talk

This talk will discuss the efforts currently in progress towards realizing an *Integrated Framework For Optimization of Wind Turbines* at DTU Wind Energy and its application to the design of a 10 MW wind turbine rotor.

- FUSED-Wind: A novel unified open source framework for MDAO of wind turbines
- AirfoilOpt2: Airfoil optimization
- HAWTOPT2: Turbine optimization

New Framework for Multi-Disciplinary Analysis and Optimization

- DTU Wind Energy has throughout many years developed software dedicated to analysis of wind turbines at many levels of fidelity.
- Many of these tools are now well consolidated, validated, and used in industry.
- DTU Wind Energy has a unique position in the field of wind energy research in that the department has experts on most disciplines involved in the design of a wind turbine.
- We have previously focused primarily on improving specific components, not the entire system.
- Consolidating all the expert knowledge and state-of-the-art software into a single cross-disciplinary framework could help break some of the barriers faced in the design of next-generation wind turbines.

New Framework for Multi-Disciplinary Analysis and Optimization

Based on previous rotor optimization codes and the design process of the DTU 10MW RWT, development of a new more versatile software for rotor optimization was started as part of the Light Rotor project funded by the Danish Energy Council (EUDP).

Requirements

- *Think beyond optimization*: A unified analysis tool can help break disciplinary barriers.
- *Simple interfaces*: We wanted to create simple to use interfaces to potentially very complex codes.
- *Changing workflows*: We wanted to be able to change around how codes are wired together to adapt to different usage scenarios.
- *User extensibility*: The user community should be able to extend the framework with their own tools.

Software Design
Based on OpenMDAO

- To systematically handle the workflow and dataflow of the potentially very complex problem formulations, the OpenMDAO framework seemed very well suited.
- OpenMDAO is developed by NASA and released as an open source package (Apache 2 license).
- OpenMDAO gives access to a large catalogue of optimizers, optimization architectures, design space exploration etc.
- Using a freely available/open source tool enables easier collaboration with other researchers and industry.

FUSED-Wind - Framework for Unified Systems Engineering and Design of Wind Turbine Plants (fusedwind.org)

Collaboration with NREL

- NREL is working towards many of the same goals as we are, and also chose to use OpenMDAO.
- This has led to a close collaboration around a jointly developed open source framework called *FUSED-Wind*.
- The framework includes pre-defined *interfaces*, *workflows* and *I/O definitions* that enables easy swapping of codes into the same workflow.
- Each organisation will release separate software bundles that target specific usages, i.e. airfoil, turbine, and wind farm optimization.

FUSED-Wind - Framework for Unified Systems Engineering and Design of Wind Turbine Plants (fusedwind.org)

FUSED-Wind Site Page News » Search

Versions

Development
0.1.dev Github

Stable
v0.1.0

Contents

- News
- Overview
- Installation
- Tutorials
- Developer Guide
- Source Documentation

Overview

Framework for Unified Systems Engineering and Design of Wind Plants (FUSED-Wind) is a free open-source framework for multi-disciplinary optimisation and analysis (MDAO) of wind energy systems, developed jointly by the Wind Energy Department at the Technical University of Denmark (DTU Wind Energy) and the National Renewable Energy Laboratory (NREL). The framework is built as an extension to the NASA developed OpenMDAO, and defines key interfaces, methods and I/O variables necessary for wiring together different simulation codes in order to achieve a system level analysis capability of wind turbine plants with multiple levels of fidelity. NREL and DTU have developed independent interfaces to their respective simulation codes and cost models with the aim of offering an environment where these codes can be used interchangeably. The open source nature of the framework enables third parties to develop interfaces to their own tools, either replacing or extending those offered by DTU and NREL.

GitHub Repository

The project source code is hosted on https://github.com/FUSED-Wind. Along with the FUSED-Wind source code, you can find the code for the examples and tutorials accompanying the documentation on this site. On github.com you can also ask questions, report bugs and request features. For a better overview of all issues and the current progress of the project visit our Waffle page.

Contacts

If you want more information about the platform, please contact the following authors

DTU: Pierre-Elouan Réthoré, Frederik Zahle,

NREL: Katherine Dykes, Peter Graf, Andrew Ning

Created using Sphinx 1.2.3.

Back to top

Interfaced DTU Wind Energy Codes

- Flow solvers: XFOIL (panel code), EllipSys2D/3D (CFD codes),
- CFD mesh generation: RotorMesher, HypGrid2D/3D,
- Noise prediction: TNO model (in-house),
- Aeroelastic codes: HAWC2, HAWCStab2,
- Structural tools: BECAS, CSProps.
- Wind resources: WAsP, FUGA, wake models (not covered here).

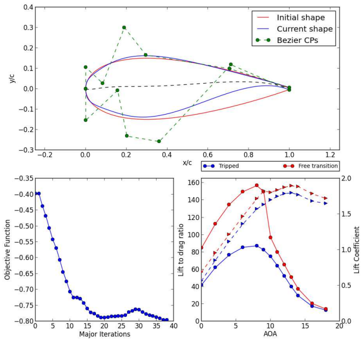
New tool for Optimization of Airfoils

Multi-Disciplinary Optimization of Airfoils

- Airfoil design has in the past mostly been focused on aerodynamic objectives, with experience-based geometric constraints to achieve other desired properties.
- While experience is crucial, it is sometimes not enough if complex multi-disciplinary trade-offs are necessary.
- Instead of imposing experience-based constraints, it is more desirable to specify direct constraints on e.g. noise emission or structural characteristics.
- A new airfoil optimization tool based on OpenMDAO was developed with interfaces to XFOIL (panel code), EllipSys2D (2D CFD solver), a TNO trailing edge noise prediction code, as well as a cross-sectional structural tool.

Airfoil Optimization Example

- Objective: maximise L/D over a range of angles of attack (3, 8, 13 deg), both clean and soiled surface.
- Design variables: aerodynamic shape Bezier control points.
- In this example the flow is solved using XFOIL.



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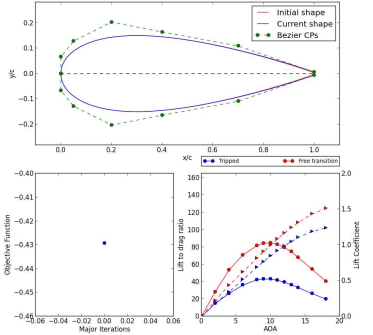
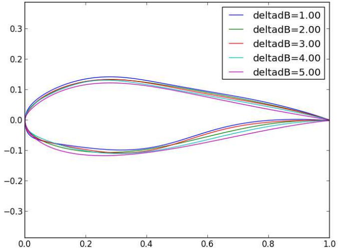


Aero-Acoustic Airfoil Optimization

- Objective: maximise L/D over a range of angles of attack (3, 8, 13 deg), both clean and soiled surface.
- Design variables: aerodynamic shape Bezier control points.
- Constraint on TE noise
- The flow is solved using XFOIL, noise predicted using the TNO model.



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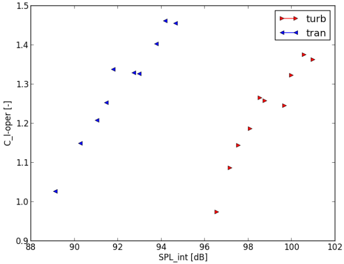

Airfoil Optimization
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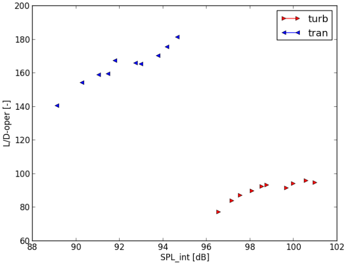

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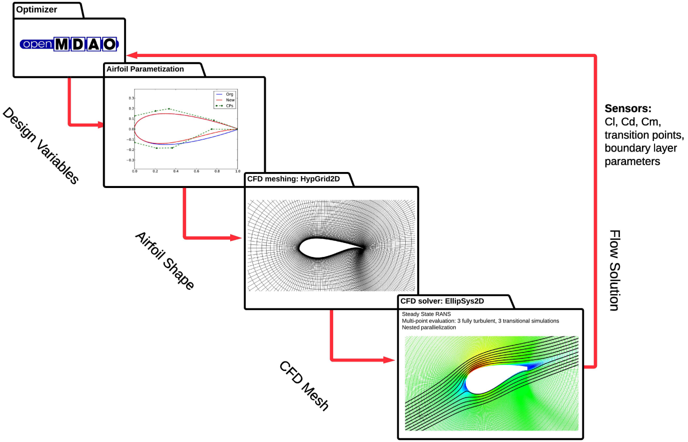
CFD-Based Airfoil Optimization

- Another aim has been to explore the potential gains of using Computational Fluid Dynamics (CFD) for airfoil optimization rather than XFOIL.
- CFD potentially offers higher accuracy, particularly for thick airfoils.
- The new optimization interface to EllipSys2D was used to design two airfoils, the LRP2-30 and the LRP2-36.
- The airfoils were recently tested in collaboration with Vestas in the Stuttgart Laminar Wind Tunnel.

Airfoil Optimization



Airfoil Optimization in the Light Rotor Project

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Airfoil Optimization in the Light Rotor Project

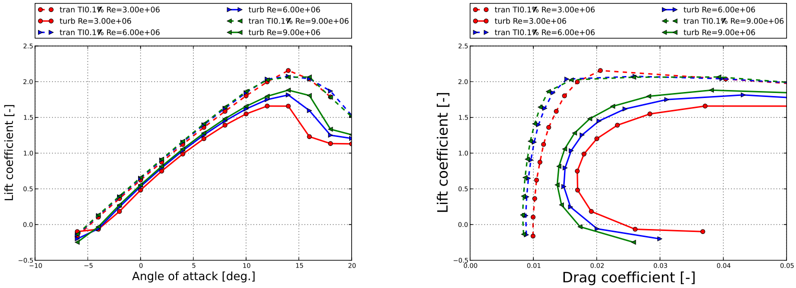

Figure: Computed lift and drag polars for the LRP2-30 airfoil at different Reynolds numbers.

Airfoil Optimization in the Light Rotor Project

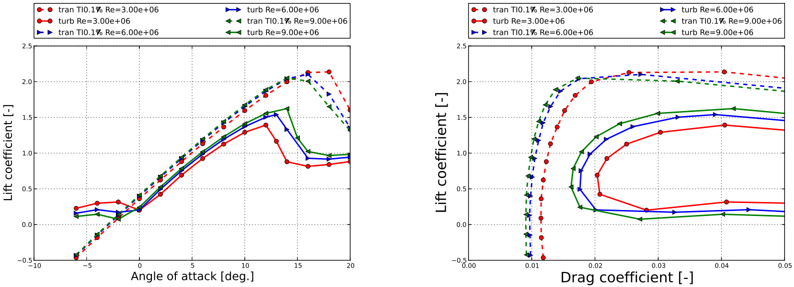

Figure: Computed lift and drag polars for the LRP2-36 airfoil at different Reynolds numbers.

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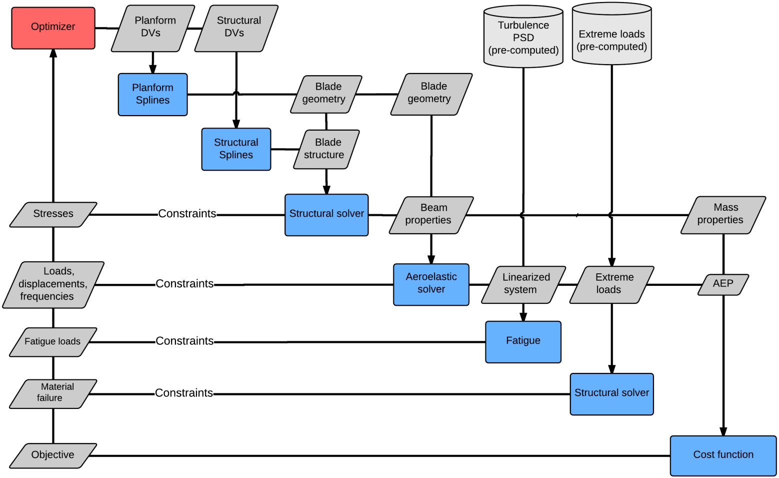
HawtOpt2: Aero-servo-elastic Optimization of Wind Turbines

Fully Coupled Aero-structural Optimization

- Simultaneous optimization of lofted blade shape and the composite structural design.
- Enables exploration of the many often conflicting objectives and constraints in a rotor design.
- Detailed tailoring of aerodynamic and structural properties.
- Constraints on specific fatigue damage loads.
- Placement of natural frequencies and damping ratios.

Blade Optimization
Optimizer Workflow Diagram



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Blade Optimization
Aero-elastic Solver: HAWCStab2

- Structural model: geometrically non-linear Timoshenko finite beam element model.
- Aerodynamic model: unsteady BEM including effects of shed vorticity and dynamic stall and dynamic inflow.
- Analytic linearization around an aero-structural steady state ignoring gravitational forces.
- Fatigue damage calculated in frequency domain based on the linear model computed by HAWCStab2.
- Controller tuning.

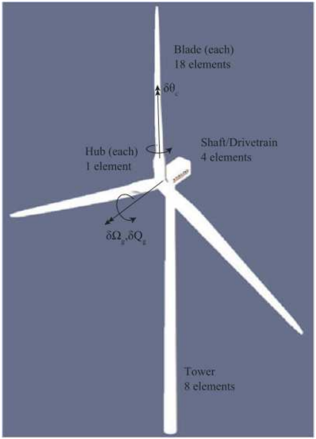

Image from: Sønderby and Hansen, Wind Energy, 2014

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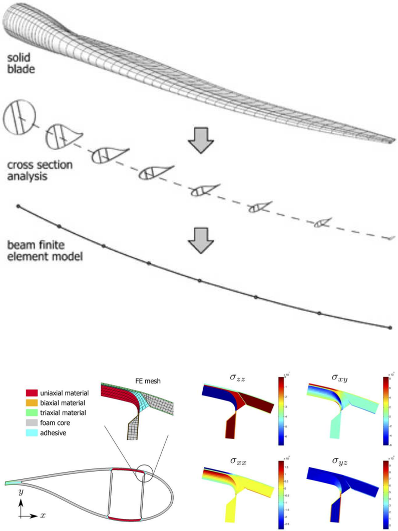
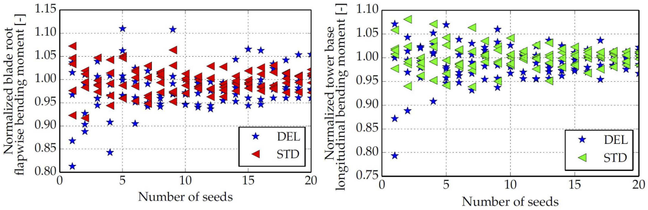
Structural Solver: BECAS (BEam Cross section Analysis Software)

- Finite element based tool for analysis of the stiffness and mass properties of beam cross sections.
- Correctly predicts effects stemming from material anisotropy and inhomogeneity in sections of arbitrary geometry (e.g., all coupling terms).
- Detailed stress analysis based on externally computed extreme loads.



Blade Optimization
Fatigue Loads with HAWC2



Each marker represents a load evaluated from a set of simulations with a defined number of turbulent seeds.

Blade Optimization
Fatigue Loads with HAWC2

- The plots show that even with a high number of turbulence seeds, the dependency of the parameters, on the set of wind realizations used in the simulations, is still high.
- At the blade root and tower base, when using 20 turbulence seeds the scatter of the loads is about $\pm 3\%$.
- This means that even with 20 turbulence seeds the wind is not fully described and the loads depend on the set of seeds selected.
- The stochastic noise in the signal deteriorates gradient estimations needed for gradient based optimization.

Fatigue Loads with HAWCStab2

- Faster than time domain;
- It predicts only fatigue loads;
- Wind spectra can be computed in the preprocessor of the optimization, so high detailed representation of the wind is obtained without compromising computational time;
- It is based on a linear model, so loads due to non-linearities are not captured;

Blade Optimization
Extreme Loads

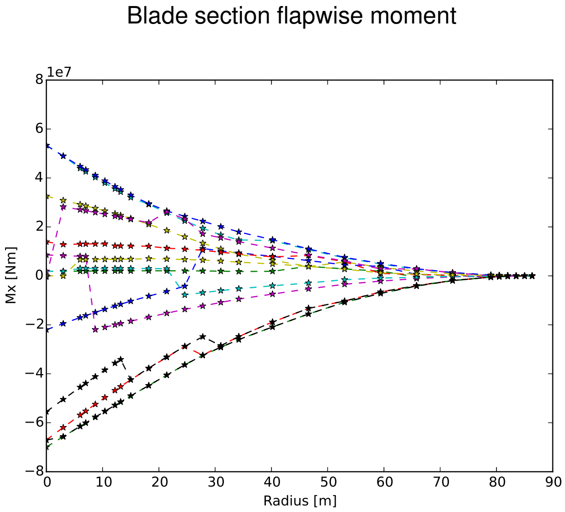
- Including time domain load case evaluations is costly and suffers from the same lack of deterministic response as for fatigue evaluations.
- We have two other options:
  - Pre-computed ”frozen” extreme loads based on starting point,
  - Simplified estimations of extreme loads, quasi-steady loads?

Extreme Loads from a quasi-steady aeroelastic solver

- 70 m/s standstill, flow from 90 deg relative to the blade chord.
- 70 m/s standstill, flow from $\pm$[5, 10, 15] deg.
- 25 m/s under operation, blade pitch stuck at 0 deg.

Blade Optimization

Extreme Loads from HAWCStab2 vs HAWC2



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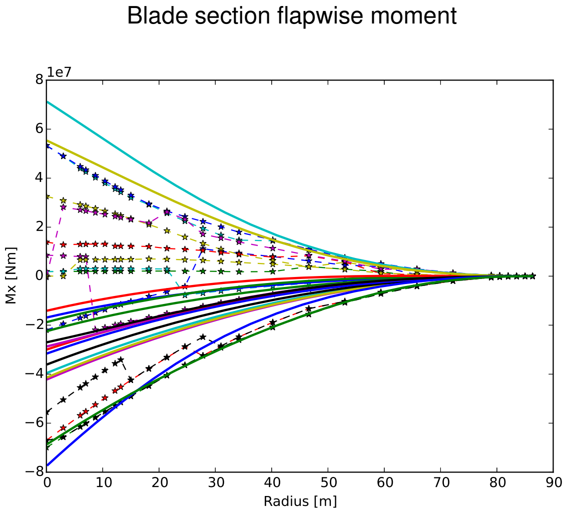
Extreme Loads from HAWCStab2 vs HAWC2



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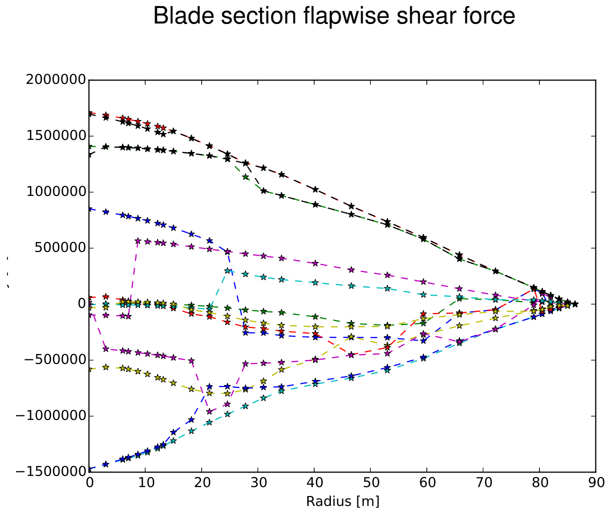
Extreme Loads from HAWCStab2



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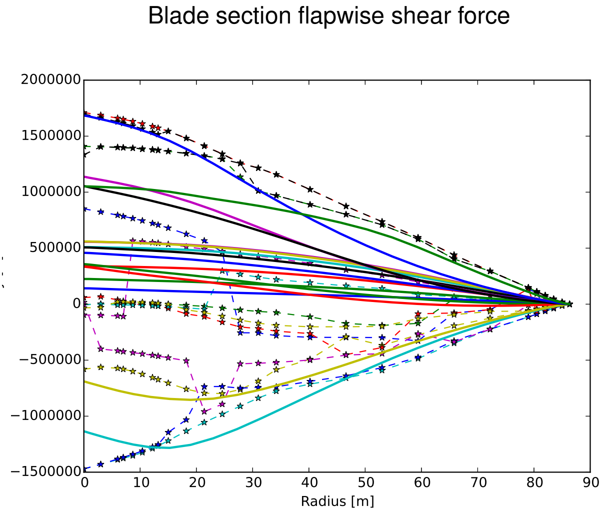

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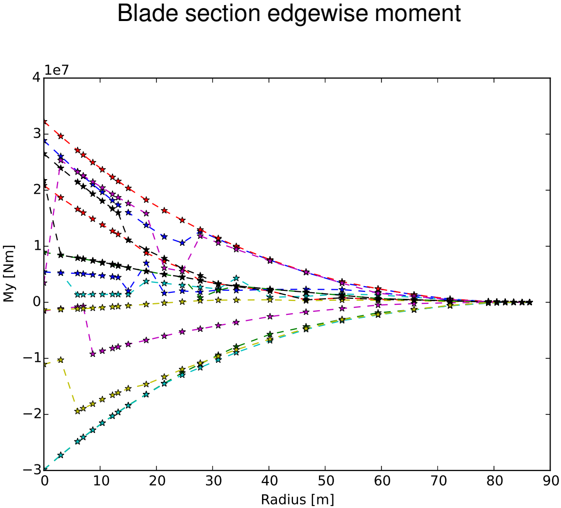

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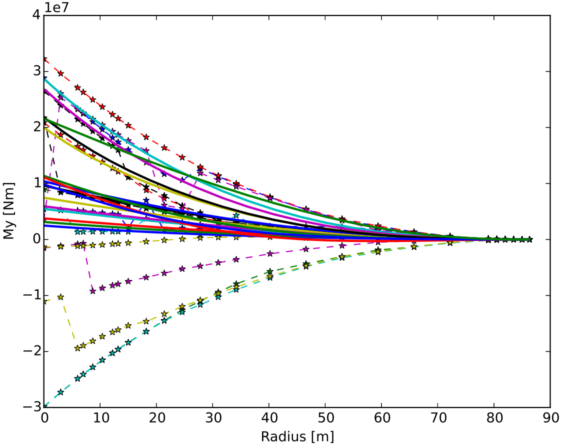
Blade Optimization
Extreme Loads from HAWCStab2

Blade section edgewise moment



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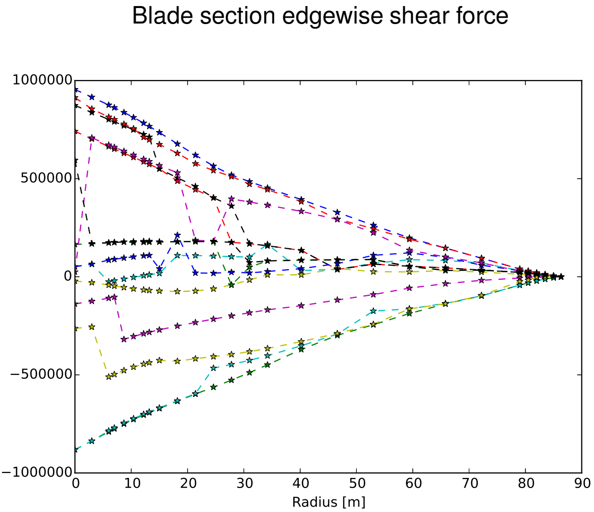

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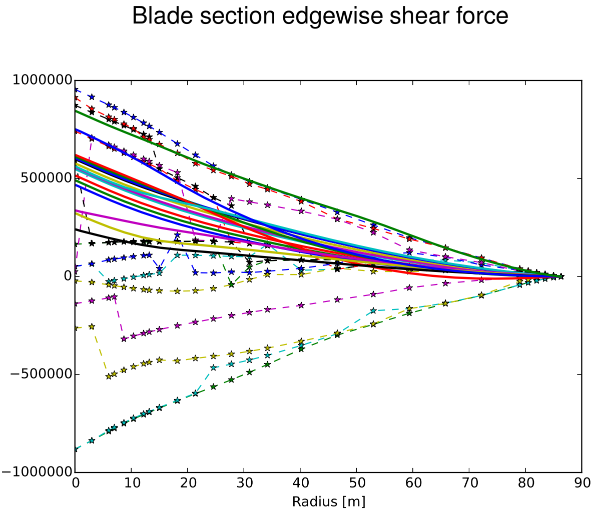

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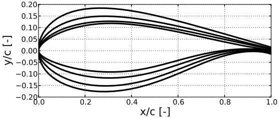
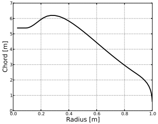
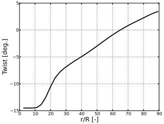
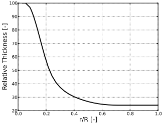
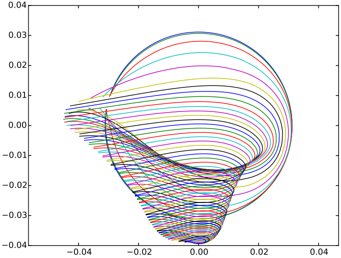
Blade Planform Parameterization





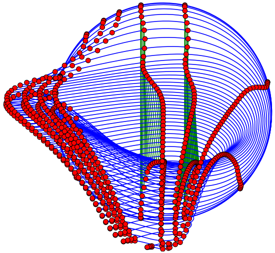


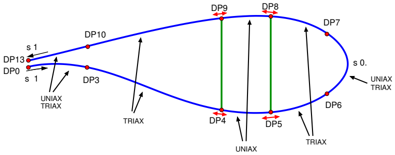




Blade Optimization
Blade Structure Parameterization

- The blade is divided into regions that cover the entire span,
- Smooth curves describing the location of division points (DPs) are simple curves with values $-1 < DP(i) < 1$,
- Shear webs attached to the spar cap DPs (at present),
- Material thickness distributions are smooth (ignoring individual plies for simplicity).
- More details at: http://www.fusedwind.org.





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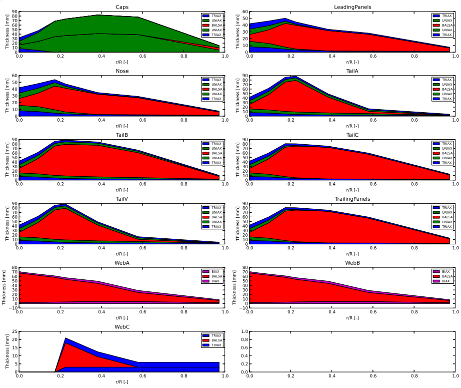
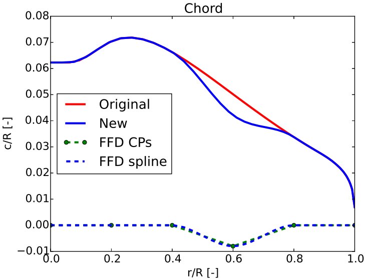
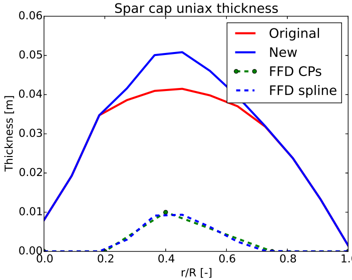


Blade Optimization

Free-form Deformation (FFD) Design Variable Splines





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Conclusions

- OpenMDAO is used as the backbone for a new framework for multidisciplinary analysis and optimization of wind turbines.
- FUSED-Wind is a new step in a direction of collaborative research and development in the field of wind turbine MDAO.
- The HawtOpt2 design tool is built around the state-of-the-art software developed by DTU Wind Energy.
- Multi-disciplinary trade-offs between mass, loads and AEP can be systematically investigated.
- Enables inclusion of frequency placement and controller tuning already in the preliminary design phase.

Question

To what extent is integrated design used in industry?

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